COST-EFFECTIVE SAMPLING of GROUNDWATER MONITORING WELLS:
A Data Review & Well Frequency Evaluation

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Abstract

Cost-Effective Sampling (CES) is a methodology for reviewing and assessing ground water data. The CES program produces a data information sheet and a lowest-frequency sampling schedule for a given groundwater monitoring location that provides the needed information for regulatory and remedial decision-making. The determination of sampling frequency for a given location is based on trend, variability, and magnitude statistics describing the contaminants at that location. The underlying principle is that a location's schedule should be primarily determined by the *rate of change* in concentrations that have been observed there in the recent past. The higher the rate of change, whether upward or downward, the greater the need for frequent sampling. Conversely, where little change is observed, a more relaxed schedule can be followed. CES was implemented at LLNL in 1992 and approved by U.S. EPA - Region IX and the local regulators. Applying the CES methodology has produced a 40% reduction in the required annual number of routine ground water samples at LLNL. This reduction has saved LLNL $390,000 annually in sampling, data management, and analysis costs.

Introduction

The initial development of the CES program at Lawrence Livermore National Laboratory (LLNL) was motivated by the preponderance of sampling results which showed little or no change in concentration over time or fell below detection limits in the 700+ groundwater monitoring wells at the laboratory's two environmental restoration sites. The fact that so many locations had shown very little change, or had ceased for some time to show, any detectable levels of contamination suggested that the 700+ groundwater monitoring wells were being sampled more often than necessary. CES was developed to not only to make sampling frequency recommendations, it was also created as a data reviewing tool. A quick process to help the project staff get a summary status report of all the chemicals of concern (COCs). The status reports include; sampling frequencies for each COC, the last sample date, the total number of samples, number of non-detects, and the overall recommendation of the specific well location. The sampling schedule is a recommendation list is a tool to aid the project staff in decisions concerning sampling frequencies of the ground water monitoring.

Locational vs. Data-Oriented Sampling Rationales

The original method for determining sampling frequencies at LLNL used the well location with respect to the contaminant plume (near or within a plume) as the deciding factor for the sampling schedule (see Figure 1). This decision process caused the majority of the wells to be sampled quarterly, even those that had shown no change over an eight-year period. The major problem with this method was that it did not account for the slow rate of migration of the contaminants on the site. Because of the slow migration, concentrations within a well have tended to remain constant.

This intra-well consistency brought about the idea of basing the sampling frequency on the changes in concentration seen at a given well, rather than that well's location with respect to the plume. CES recommends sampling frequencies based on quantitative analyses of the trends in, and variability of, important contaminants at a given monitoring location. It then interprets this information by means of decision trees to arrive at a desired sampling frequency. An essential aspect of the system is its ease of interpretation. The goal has been to keep to widely understood statistics that fit into decision-logic familiar to people involved with environmental chemistry.

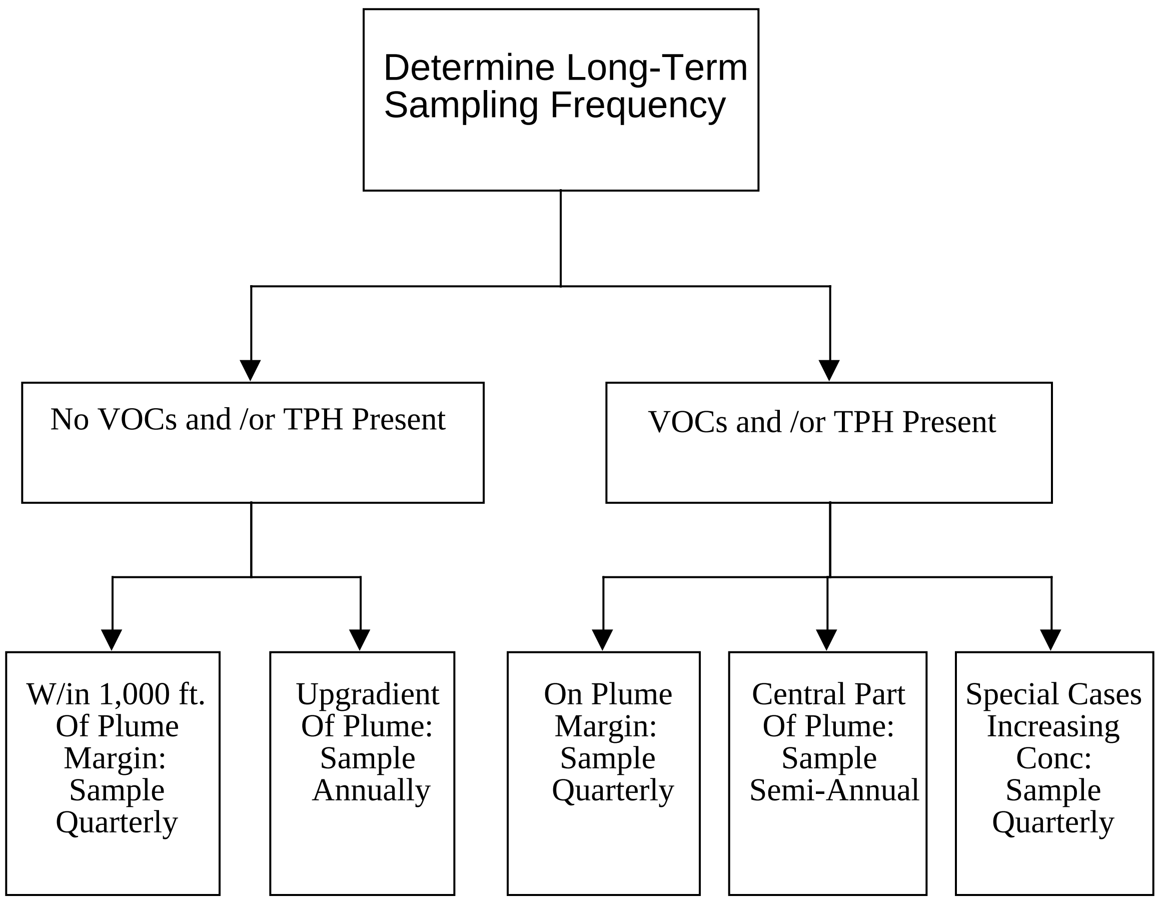

Figure 1. Location-Oriented Method of Setting Sampling Frequencies.

The determination of sampling frequency for a given location is based on trend, variability, and magnitude statistics describing the contaminants at that location. The underlying principle is that a location's schedule should be primarily determined by the *rate of change* in concentrations that have been observed there in the recent past. The higher the rate of change, whether upward or downward, the greater the need for frequent sampling. Conversely, where little change is observed, a more relaxed schedule can be followed.

A second rationale for more frequent sampling is the *degree of uncertainty* displayed in the measured concentrations. Low overall rates of change can be offset by a higher degree of variability, requiring that a more frequent schedule be maintained to better define the likely degree of contamination at that location. On the other hand, a high rate of change that is highly predictable warrants a lower sampling frequency.

Finally, the *magnitude* of the measured concentrations affects the interpretation that is placed on rates of change. Clearly, a yearly change of 50 parts per billion (ppb) means something quite different when the median concentration is 10 vs. 1000. The significance of the absolute concentrations also varies by compound. The hazard associated with a 300 ppb concentration of TCE is interpreted differently from a 300 ppb concentration of chloroform.

A limited amount of statistical guidance is available for sites wishing to reduce their sampling schedules in a non-arbitrary manner. EPA documents written for RCRA facilities (U.S. EPA, 1992) suggest using techniques such as Darcy's Equation to estimate the time between independent samples of groundwater based on the physics of flow. A second EPA publication presents a method for estimating sampling intervals from a combination of a first-order autoregressive model of groundwater time series data and the standard error of that series (Barcelona et al., 1989). A third, and especially interesting, approach is the creation of temporal variograms to estimate time correlations among samples in the same way that spatial variograms are used to estimate spatial correlations (Tuckfield, 1994). All the above approaches are geared toward determining the time-interval at which statistical independence is achieved. This is a key assumption to the proper application of standard significance tests and also provides a logical foundation on which to base sampling frequencies. However, these more purely statistical approaches to the sampling frequency problem have more difficulty-gaining acceptance because of the highly specialized knowledge required to properly implement them.

Decision Logic Charts – Implemented Version

A few issues must be clarified before proceeding to a discussion of the logic contained in the flow charts in Figures 2, 3, and 4. The first of these involves the available scheduling options. In the future, it is expected that fairly precise estimates of needed frequency, down to a resolution of weeks, will be made. This precision will become important when scheduling to assess the effects of remedial actions is incorporated into the system. For the time being, however, only compliance monitoring is being addressed. So, the scheduling options have been restricted to a multiple of the traditional quarterly sampling: quarterly, semi-annual, and annual.

Second, each scheduling category has been associated with a base rate of change. The annual category is reserved for trends of less than 10 ppb per year. The quarterly category is associated with rates of change in excess of 30 ppb per year. The semi-annual category falls in the range of 10 - 30 ppb per year. However, high and low degrees of variability can move a particular location out of the semi-annual and into the quarterly or annual categories. The currently used cut-offs have been tailored to 11 VOCs of particular interest at LLNL (Carbon tetrachloride, chloroform, 1,1-DCA, 1,2-DCA, 1,1-DCE, 1,2-DCE, Freon 113, PCE, 1,1,1-TCA, TCE, and Freon 11), HMX and RDX, 7 metals (arsenic, barium, copper, lead, nickel, uranium, and zinc) and tritium. The low rates of change for the cutoffs that often seen at arid sites. In the version under development, a more generally applicable scheme for setting cut-offs is being employed.

The overall flow of CES is shown in Figure 2. To be eligible for consideration, a location (usually a groundwater monitoring well or piezometer) must have already been sampled on at least six occasions, which is roughly equivalent to 18 months of quarterly sampling. Newly installed wells must be sampled frequently to build up a history for the purposes of analysis. The decision-rules of the system are applied independently to each contaminant in the target list for a particular location. The schedule assigned to the location is the most frequent schedule estimated for any individual contaminant.

The evaluation of each contaminant proceeds in three steps. First, an initial estimate of the desirable schedule is obtained by analyzing the most recent trend and variability information. In step 2, the recent trend is compared with the overall, or long-term trend, to identify cases where the step 1 decision should be overridden by an estimate based on overall statistics. In step 3, a correction is made for the less toxic substances on the list. Even though their yearly rates of change may be relatively high, their estimates are revised downward so long as the magnitude of the concentrations involved fall below certain limits. Finally, all CES recommendations are subject to change as a result of scientific and engineering review. Common reasons for overriding recommendations are anticipation of future remedial actions and public relations considerations pertaining to off-site locations.

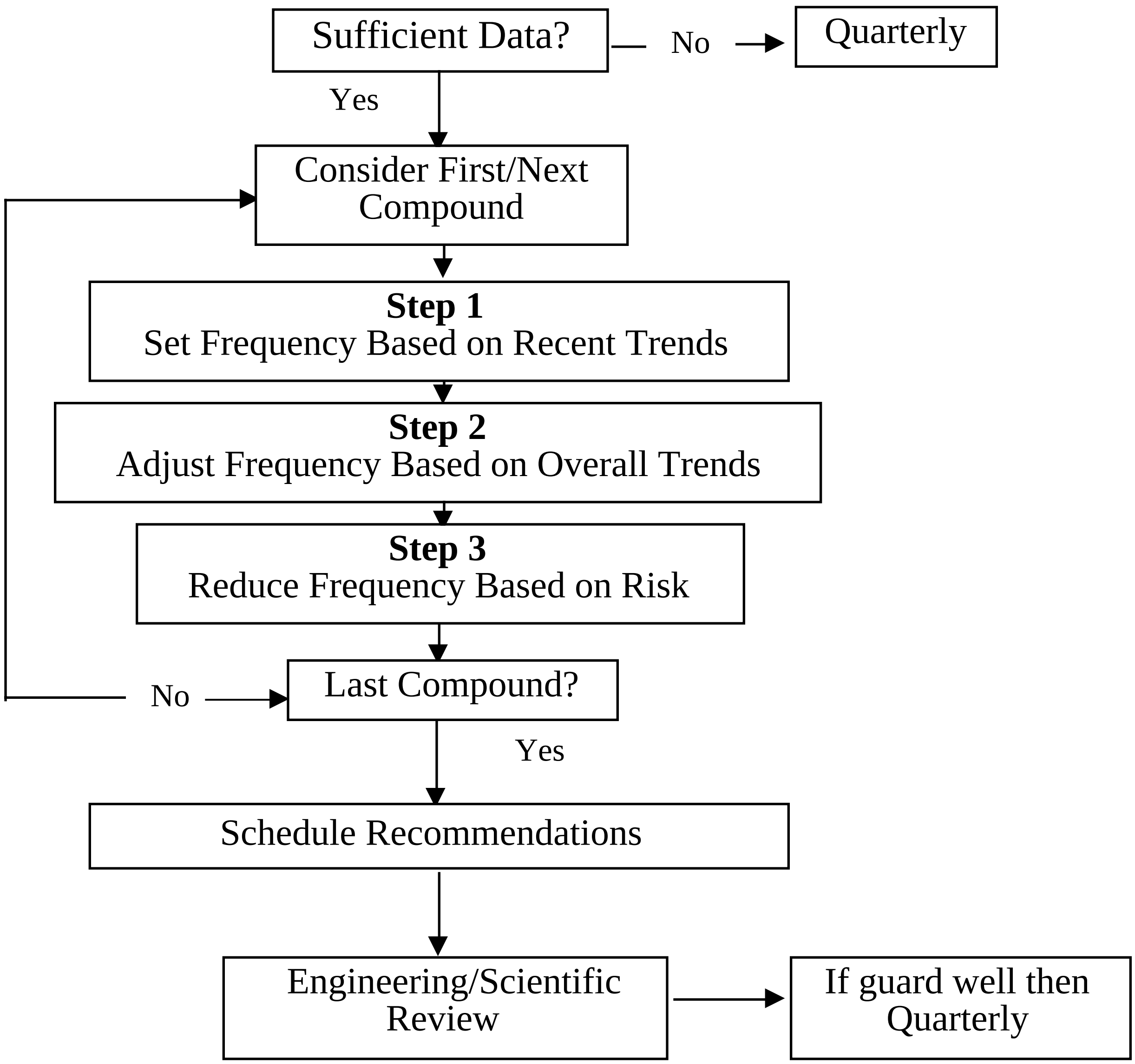

Figure 2. Overview of Steps in CES

Step 1: As was mentioned earlier, the primary focus of CES is on trends or rates of change. This is currently defined as the least-squares slope obtained by regressing time against measured concentrations. The advantage of this statistic is its ease of interpretation. The slope can be expressed as a yearly change in concentration. Its disadvantage is that its suitability for use with non-normal data is questionable. Part of this problem could be solved by linearizing the data by means of a natural log transformation. However, this introduces interpretation problems which, for this first simple version of CES, we are trying to avoid.

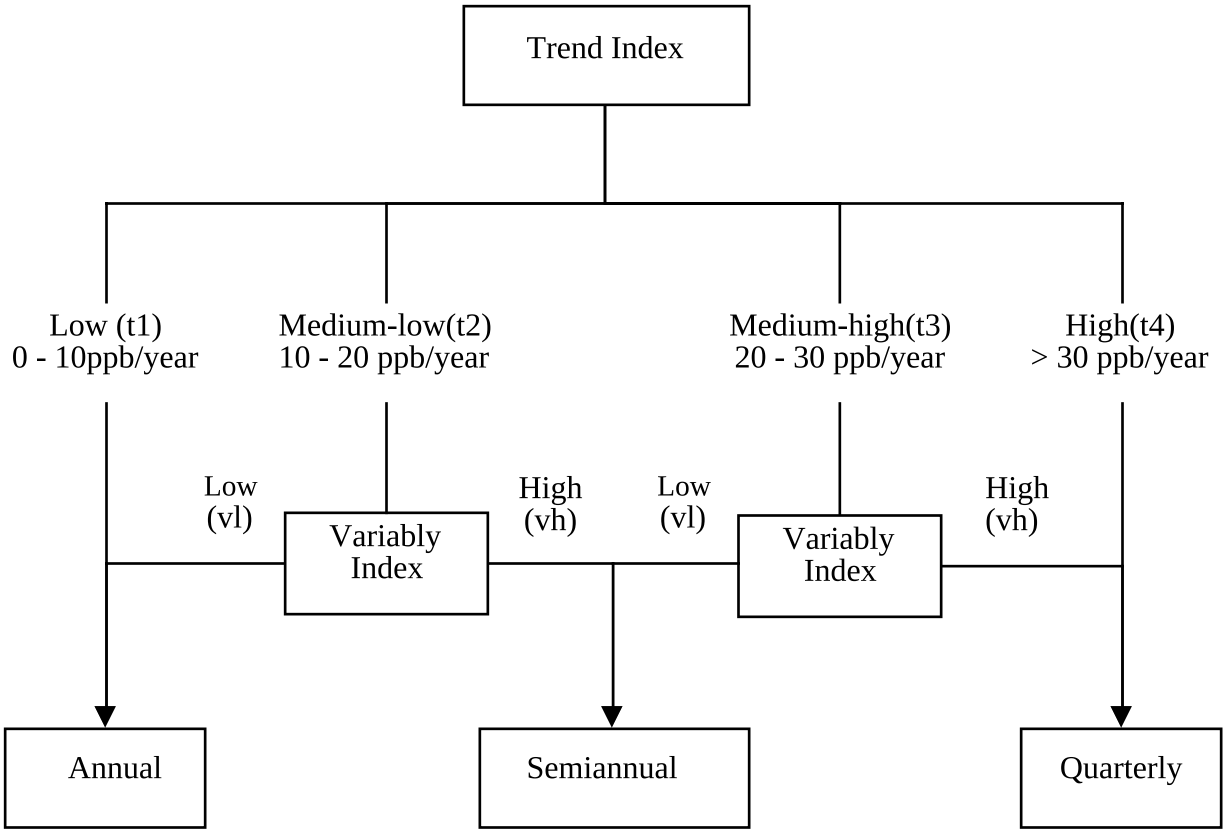

Figure 3. Step 1 : Set Frequency Based on Trend and Variability

Rate, rather than direction, of change is the dominant factor. All rate and rate-related statistics use absolute values. Based on the rate of change information, a location is routed along one of four paths (see Figure 3). The lowest rate, 0-10 ppb per year, always leads to an annual frequency schedule. The highest rate, 30+ ppb per year, always leads to a quarterly schedule. Rates of change in between these two extremes are qualified by variability information, with higher variability leading to a higher sampling frequency.

Variability is characterized by a distribution-free version of the coefficient of variation: the range divided by the median concentration. This statistic corrects for the influence of magnitude on variability, which is an important consideration given that the range of concentrations in VOCs routinely varies over three orders of magnitude. The cut-off of 1.0 distinguishing high vs. low variability was derived empirically from the data distributions. It is the median value of that statistic calculated for the two most active contaminants at LLNL, TCE and PCE, across all locations in a benchmark dataset. Both the trend and variability statistics in Step 1 are calculated from the 6 most recent sampling periods’ worth of data.

Step 2. While emphasis is placed on setting frequencies from recent data, there are cases where a long-term history of change may override the Step 1 decision. The first three boxes in the Step 2 flow chart (see Figure 4) weed out cases where such a re-evaluation is undesirable or trivial. The goal is to examine only those cases where the overall rate of change is significantly greater than the recent rate of change.

The major branch in Step 2 is meant to distinguish two ways in which the overall trend may be significantly greater than the recent trend. The right-hand side considers the majority of cases. The overall trend is definitely, but not extremely, greater than the recent trend: so the sampling frequency is re-estimated using Step 1 logic, but with overall rather than recent statistics.

The left-hand side considers the situation where the recent trend is very flat relative to the overall trend. If the flattening occurs at a low level of concentration, the Step 1 decision is retained. If not, the decision is left to scientific/engineering judgment.

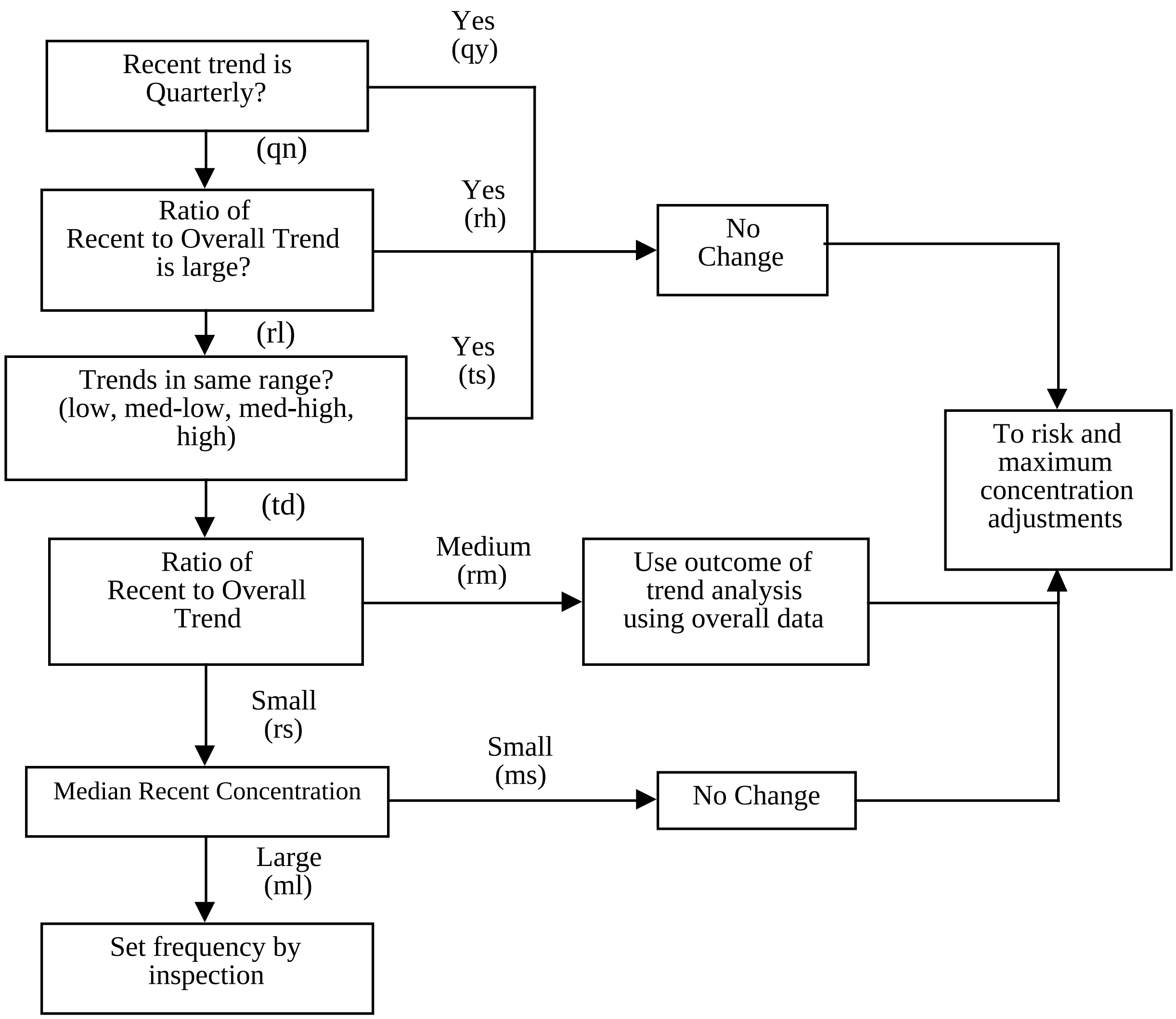

Figure 4. Step 2 of CES – Adjustments Based on Recent Vs. Overall Trends

Step 3. Not all compounds in the target list are equally harmful. Because of differences in drinking water standards, an average trend of 25 ppb/year for TCE is far more serious than the same trend for Chloroform or the two forms of Freon. So, quarterly and semi-annual decisions are reduced one level if the maximum concentration in the recent set of samples is less than 1/2 of the compound's MCL.

Cost Savings - Implemented

The table below presents the sampling status of monitoring wells at LLNL's restoration sites both before and after the initial application of CES.

	Sampling Schedule		
	Quarterly	**Semi-annual**	**Annual**
Before CES	418	112	24
After CES	216	124	214

It is estimated that this 40% reduction in the number of samples taken at the main site have saved $390,000 annually in sampling, data management, and analysis costs.

Recent Additions to the CES Program

In 1997, two additions were made to the CES program. The first addition allows for the option of biennial (a sampling frequency of once every two years) sampling. The criterion for this decision is 3 consecutive annual recommendations. The second adjustment is the addition of decision logic to address higher concentrations. The program was initially designed to address wells with concentrations for each analyte lower than 250 ppb. The program can now evaluate concentration ranges up into the high ppm levels. The high concentration evaluations and recommendations are done by using adjusted cut-offs designed specifically for the analyte and the concentration ranges of interest.

References

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